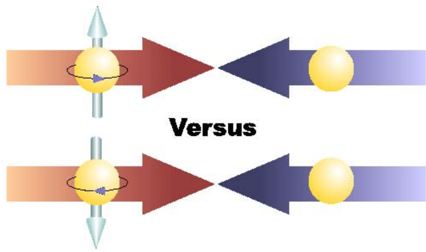
Polarimetry at RHIC

A. Bravar, I. Alekseev, G. Bunce, S. Dhawan, R. Gill,
W. Haeberli, H. Huang, G. Igo, O. Jinnouchi, K. Kurita, A. Khodinov,
Z. Li, Y. Makdisi, A. Nass, H. Okada, S. Rescia, N. Saito, H. Spinka,
E. Stephenson, D. Svirida, D. Underwood, C. Whitten,
T. Wise, J. Wood, A. Zelenski

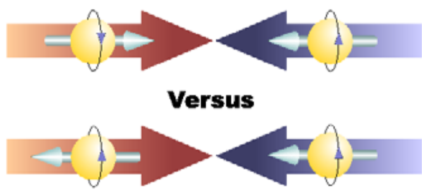
BROOKHAVEN NATIONAL LABORATORY

Polarimetry : Impact on Spin Physics

Single Spin Asymmetries



Double Spin Asymmetries



Physics Asymmetries

$$A_N = \frac{1}{P_B}\left(\frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}\right)$$

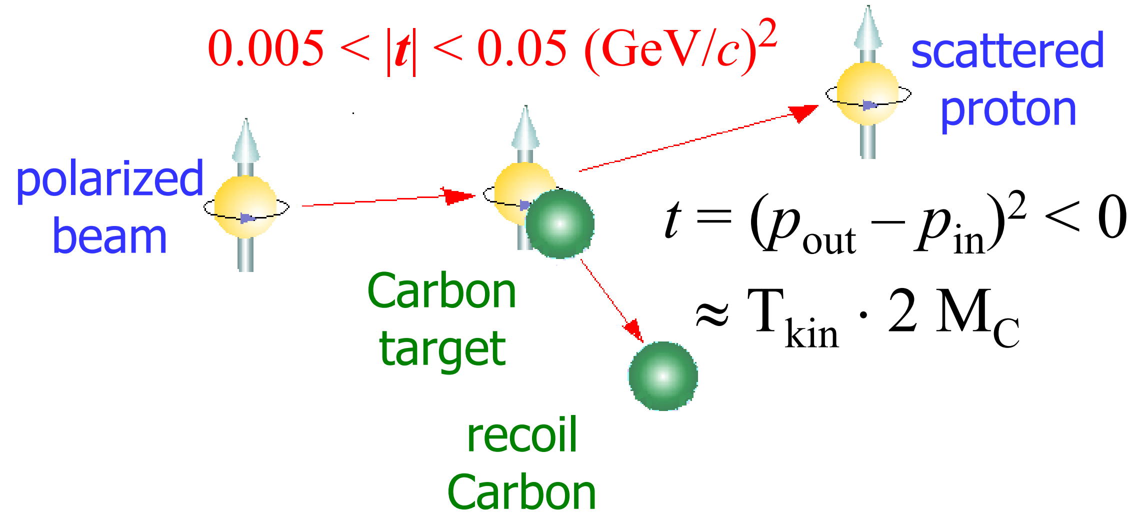
$$A_{LL} = \frac{1}{P_B{}^2}\left(\frac{N_{\uparrow\uparrow} - N_{\uparrow\downarrow}}{N_{\uparrow\uparrow} + N_{\uparrow\downarrow}}\right)$$

- measured spin asymmetries normalized by P_B to extract Physics Spin Observables
- RHIC Spin Program requires $\Delta P_{beam} / P_{beam} < 0.05$
- normalization ⇒ scale uncertainty
- polarimetric process with large σ and known A_N
  - *pC* elastic scattering in CNI region
  - A_N almost calculable, but small ~ 1 – 4 %
  - absolute "calibration": elastic *pp* scattering with polarized gas-jet target

Elastic $pC \to pC$ scattering at low t

$$A_N = -\frac{1}{P_B} \cdot \frac{N_{left} - N_{right}}{N_{left} + N_{right}}$$

recoil



1. A_N from interference of spin non-flip and spin flip (helicity) amplitudes
   $\Rightarrow$ spin dependence of interaction
   $\Rightarrow$ hadronic spin flip (spin-coupling of Pomeron)

2. Polarimetry
   – almost "calculable"
   – small $A_N \sim 1 – 4\ \%$ $\Rightarrow$ requires large statistics $> 10^7$
   – large cross section
   – weak beam momentum dependence ($p > 20$ GeV/c) ?

A_N: from where does it come?

$$\sigma = |A_{\text{hadronic}} + A_{\text{Coulomb}}|^2 \qquad (|\mathbb{P} + \gamma|^2)$$

around $t \sim -10^{-3}$ $(\text{GeV}/c)^2$ $A_{\text{hadronic}} \approx A_{\text{Coulomb}} \Rightarrow$ INTERFERENCE

CNI = Coulomb – Nuclear Interference

unpolarized $\Rightarrow$ clearly visible in the cross section $d\sigma/dt$ (charge)

polarized $\Rightarrow$ left – right asymmetry A_N (magnetic moment)

$$A_N = C_1 \Phi_{em}^{flip} \Phi_{had}^{non-flip} + C_2 \Phi_{had}^{non-flip} \Phi_{had}^{flip}$$

$\propto(\mu-1)_p$ $\qquad$ $\propto\sqrt{\sigma^{pp}_{\text{had}}}$

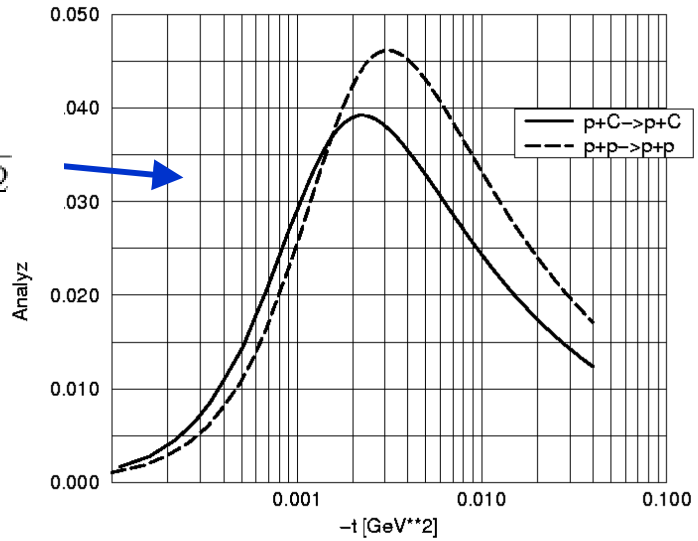
QED $\Rightarrow$ "calculable", expect $A_N \neq 0$ up to 4 – 5%

$$A_N^{int} = \sigma_{tot} \times \frac{\alpha}{m_p\sqrt{-t}} \frac{\mu_p - 1}{2} \frac{1}{\sigma_{tot}^2/16\pi + 4\pi\alpha^2/t^2}$$

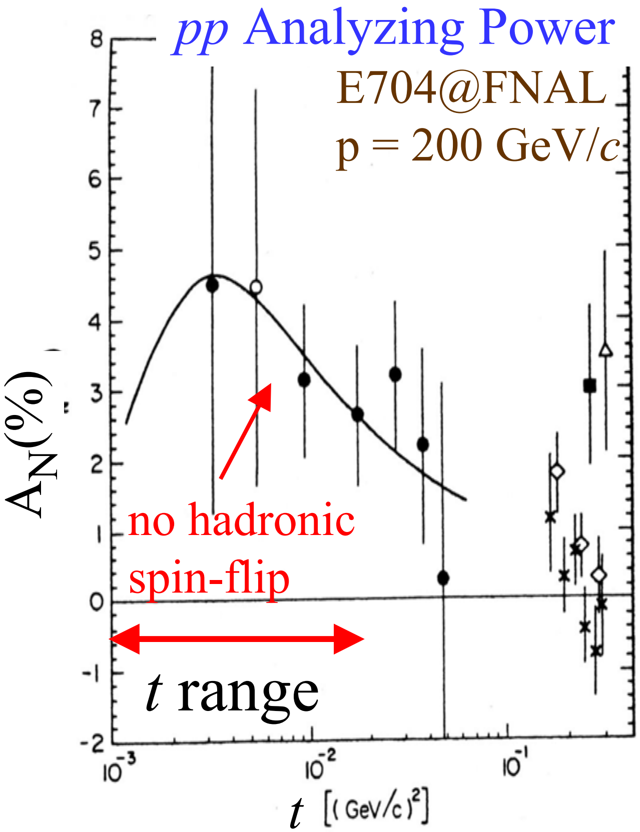
hadronic non-flip $\qquad$ EM spin flip

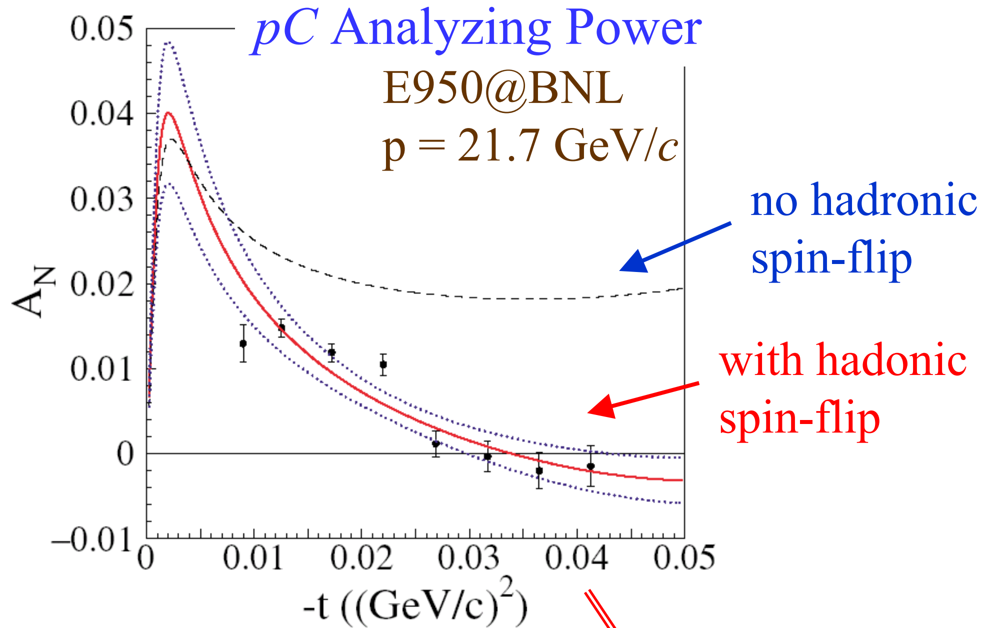
QCD $\Rightarrow$ "unpredictable", need direct measurement

$$\frac{\mu_p - 1}{2} \rightarrow \frac{\mu_p - 1}{2} - I_5 + \frac{\mu_p - 1}{2} I_2$$



Some A_N measurements in CNI region





if used for polarimetry

$\Rightarrow \Delta P/P \sim 15 - 20\%$

$r_5^{pC} \propto F_s^{had} \,/\, Im\, F_0^{had}$

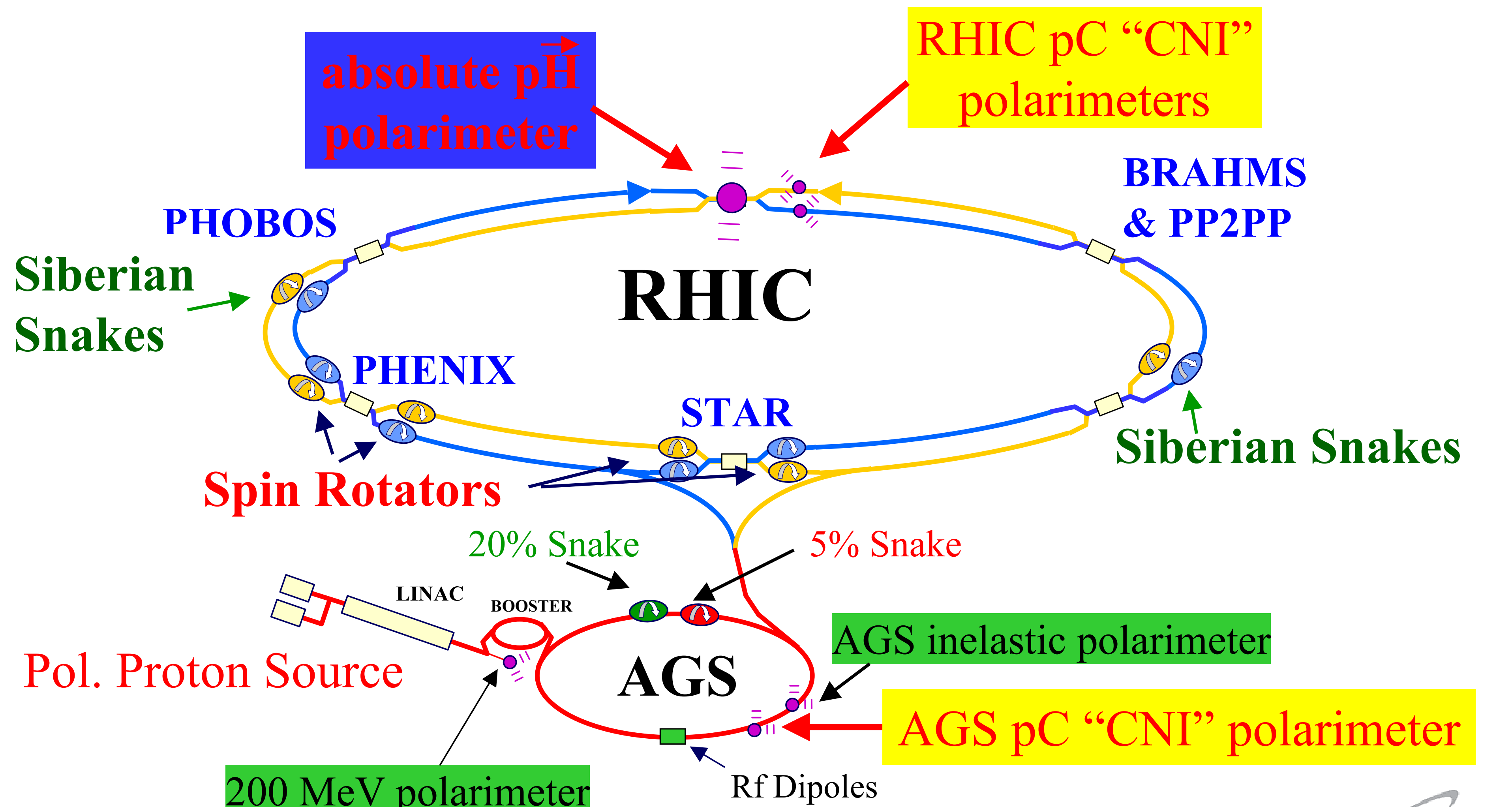
$Re\, r_5 = \quad 0.088 \pm 0.058$

$Im\, r_5 = -0.161 \pm 0.226$

highly (anti-)correlated

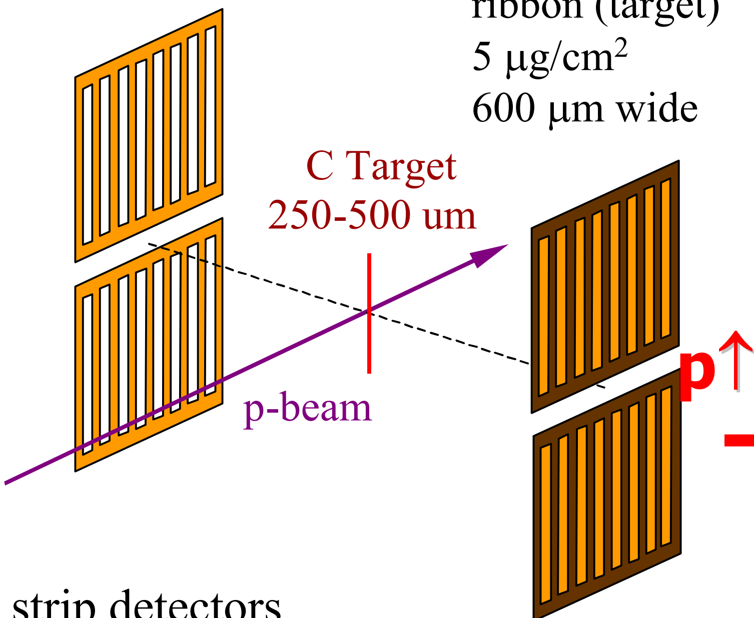
RHIC: the "Polarized" Collider

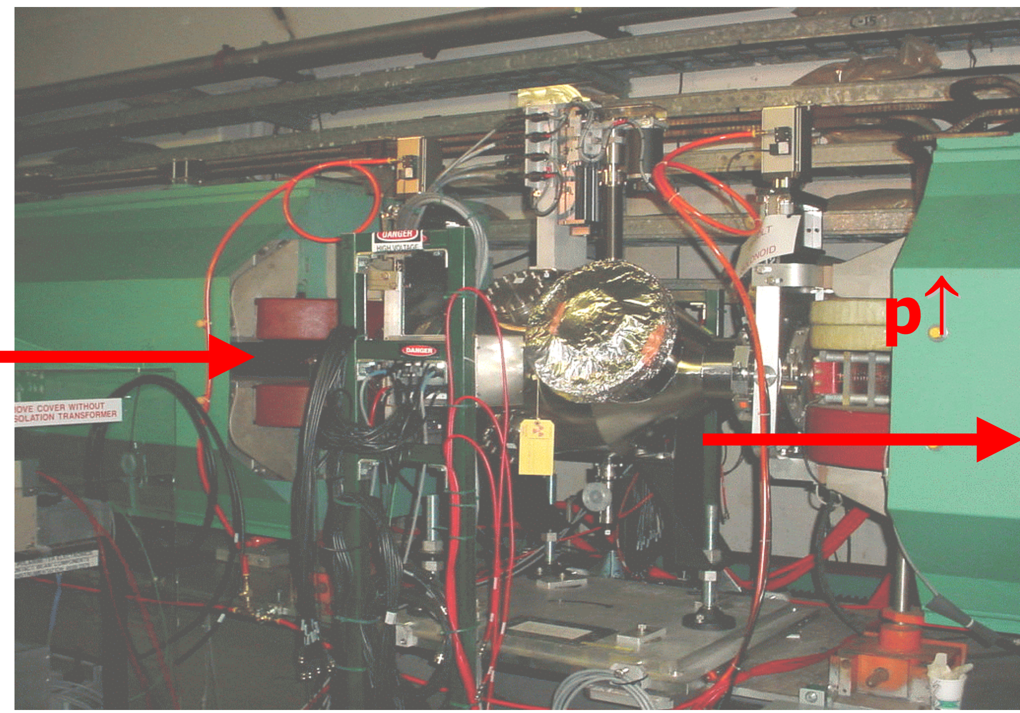
70% Polarization $L_{max} = 2 \times 10^{32}\ s^{-1}cm^{-2}$ $50 < \sqrt{s} < 500$ GeV



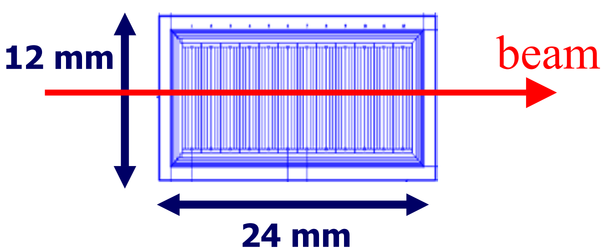
Elastic $p\uparrow$C Scattering Setup in the AGS Ring

ultra-thin Carbon ribbon (target)
5 $\mu g/cm^2$
600 μm wide



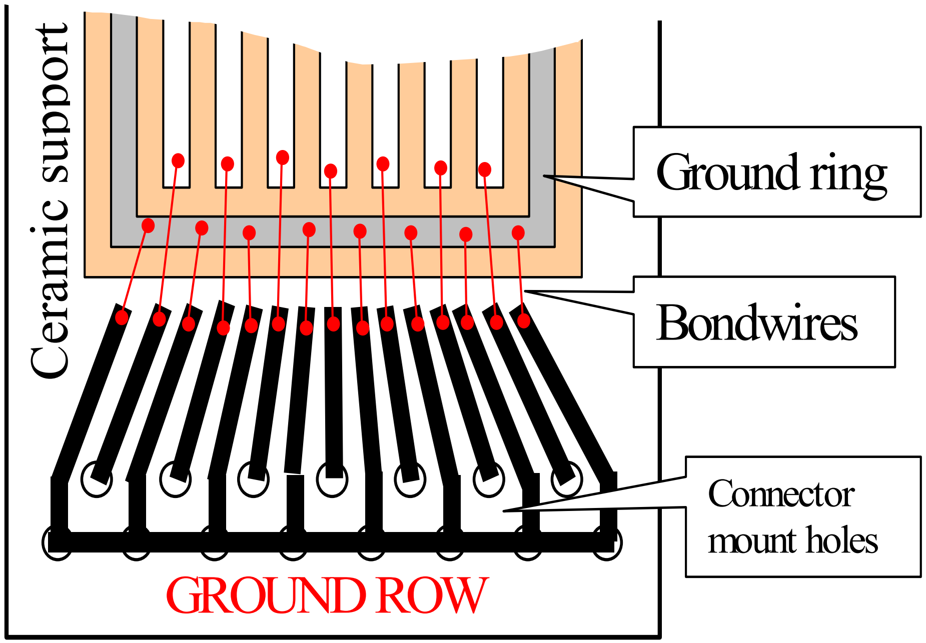


Si strip detectors
12 vertical strips



similar setups in RHIC for each beam

No More Beam Induced Pickups…

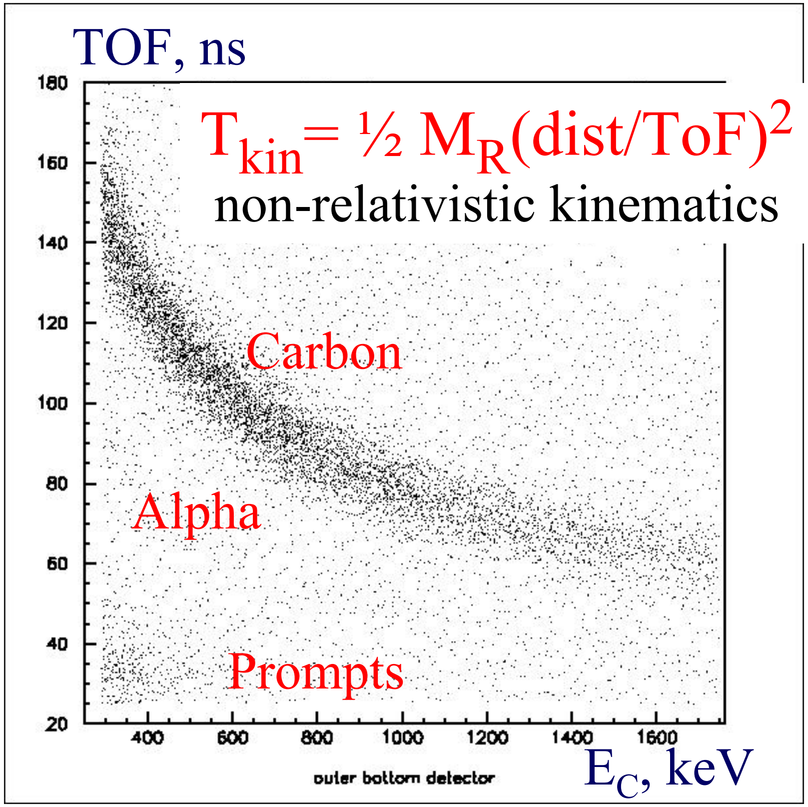


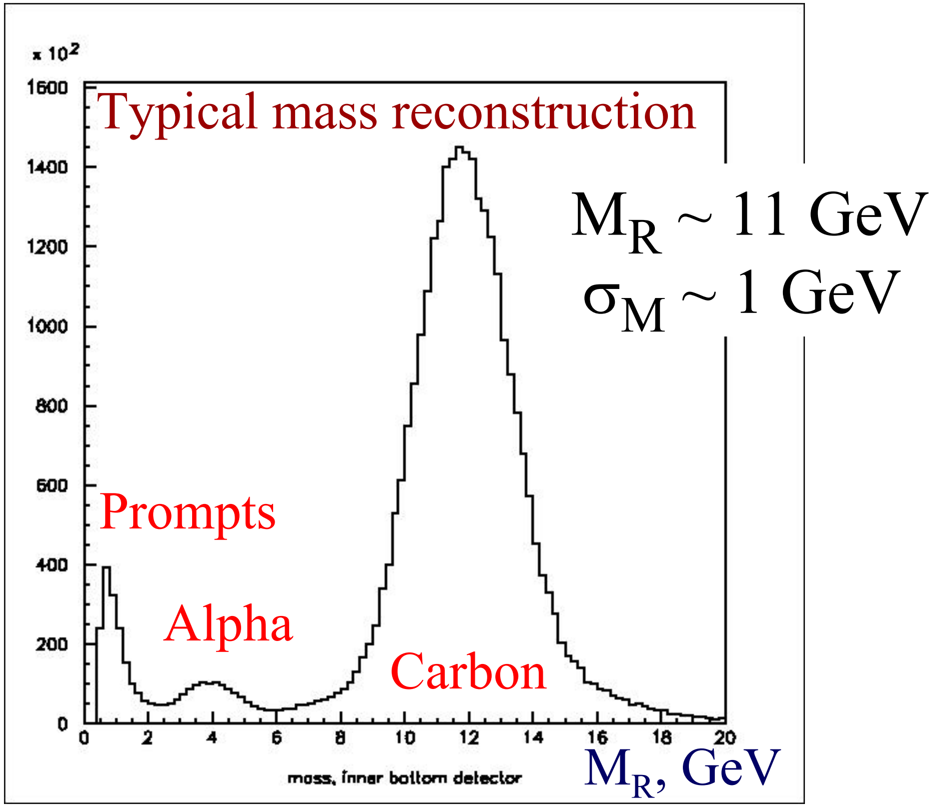
NO BEAM CHARGE INDUCED SIGNAL !!!

(Up to $2 \cdot 10^{11}$ p/bunch)

- Top secret: every second line IS GROUND the whole way down to the very strip
- No pileup in the preamp
- Lower limit in $-t$ is only by the detector noise
- No upper limit on $-t$
- Can see real relativistic (fast) particles from the target – good T_0 definition (the rate is of the same order as carbons or higher)

Performance





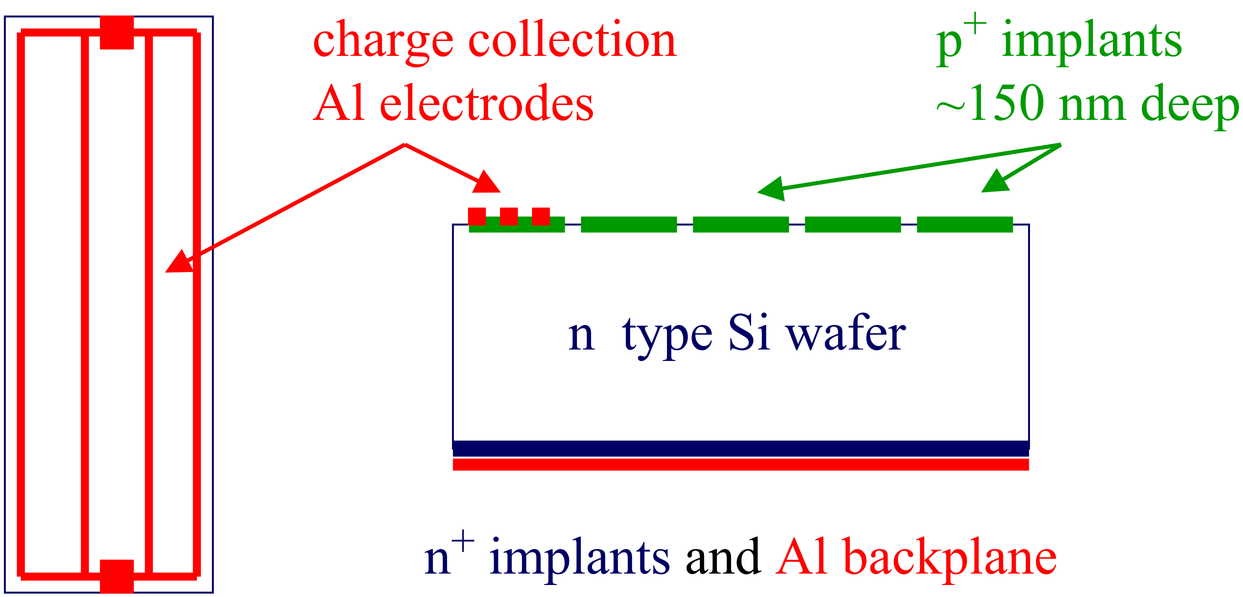
- Very clean data
- Good separation of carbon from prompts may allow going to very high $-t$ values
- Low χ^2 of sequential measurements – stable operation

Si Detector and Energy Loss

at $\boldsymbol{t} \sim -0.01\ (\mathrm{GeV}/c)^2$, Energy of recoil Carbon $E_{kin} \sim$ few 100 keV
($E_{kin} = -\boldsymbol{t} / 2M_C$)

range in Silicon, only fraction of micrometer
substantial fraction of Carbon energy lost in dead layer (entrance window)
correct E_{kin} for energy loss → energy scale error

important to minimize energy losses in dead layer of detector



top view of Si strip

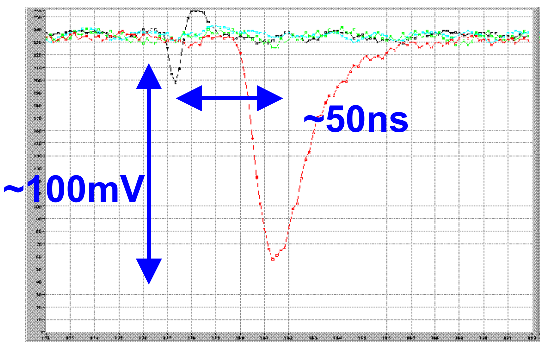
n^+ implants and Al backplane

active area
$24 \times 12\ \mathrm{mm}^2$

thickness
400 μ

12 2 mm wide
DC coupled strips

DAQ and WFD



ADC
3×140 MHz

synchronized to accelerator clocks
bunch ×-ing ⇒ "start" TDC

FPGA

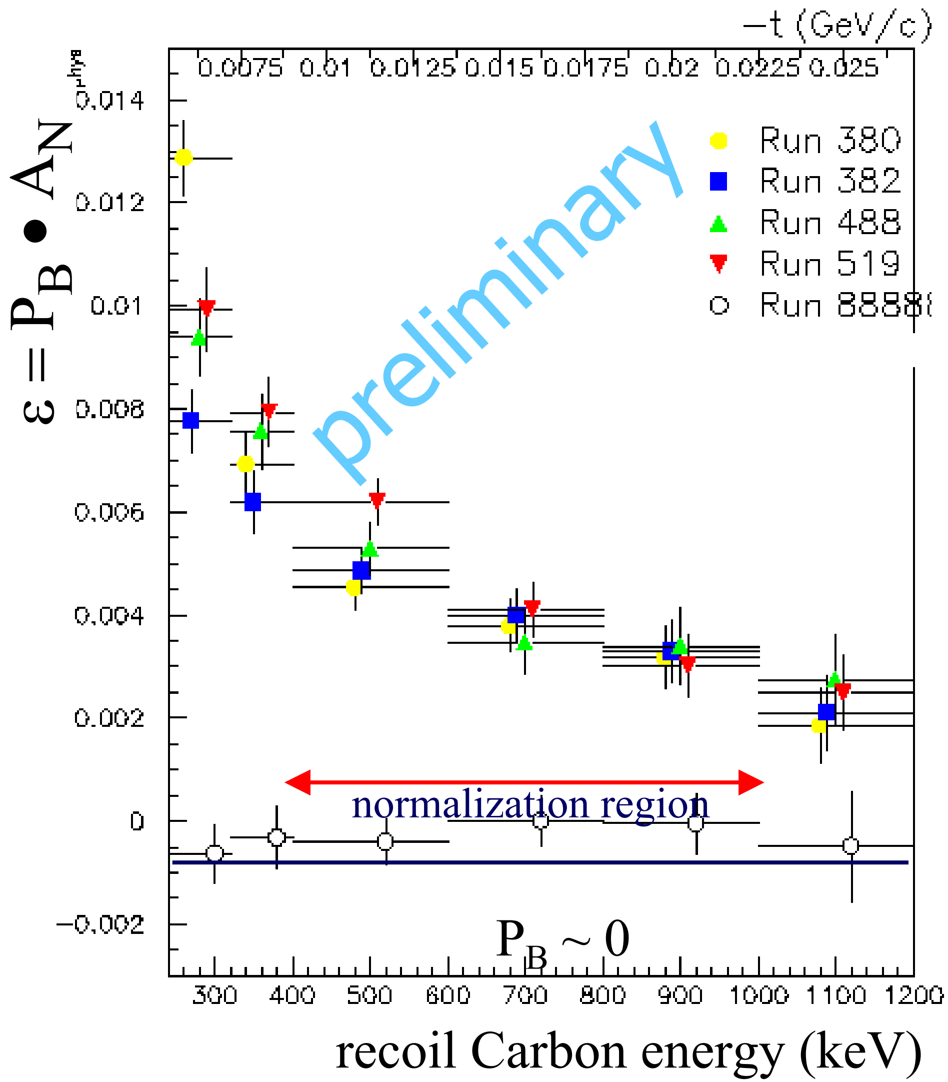
"online" analysis of waveform
performed beteween consecutive
bunch ×-ing
⇒ PH, tot Q, t.o.f

onboard memory → DAQ PC

$\Delta t \sim 2$ ns
$\Delta E < 50$ keV

Wave Form Digitizer = peak sensing ADC, CFD, …
deadtimless DAQ system ⇒ no spin dependent dead time !
can accept, analyze, and store 1 event / each bunch ×-ing
event rate: up to 10^5 ev/ch/sec

$p\uparrow C$ *raw* asymmetry at 24.3 GeV



$$P_{beam} = \frac{1}{\langle A_N \rangle} \cdot \varepsilon_N$$

$$\langle A_N \rangle = \frac{\sum N(t_i) A_N^{th}(t_i)}{\sum N(t_i)}$$

calculated over several ***t*** bins

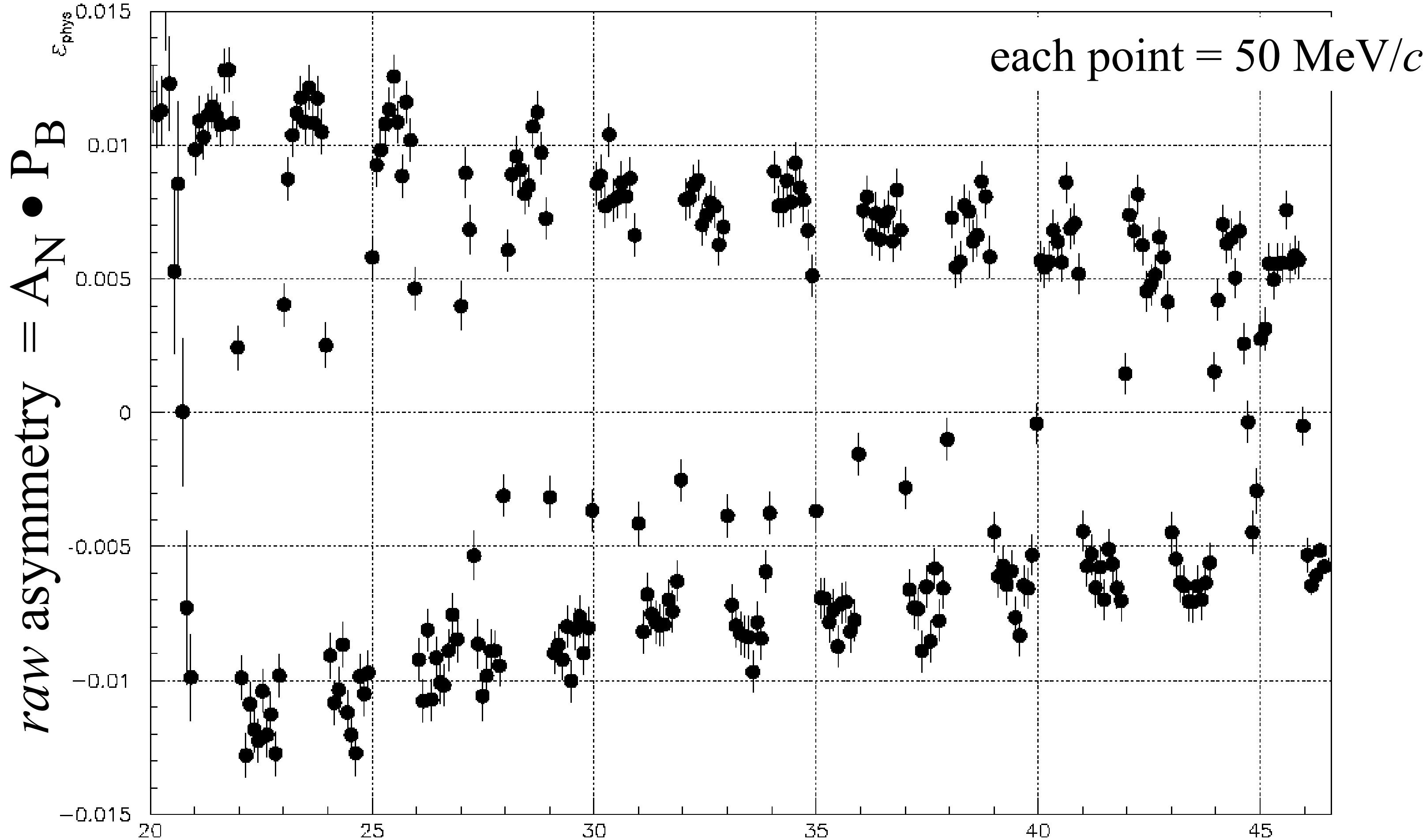
A_N^{th} from a fit to E950 data at 21.7 GeV over similar ***t*** range

L. Trueman hep-ph/0305085

$\langle A_N \rangle \approx 1.12$

$0.009 < |t| < 0.022$ (GeV/c)^2

AGS Polarization during acceleration (ramp)



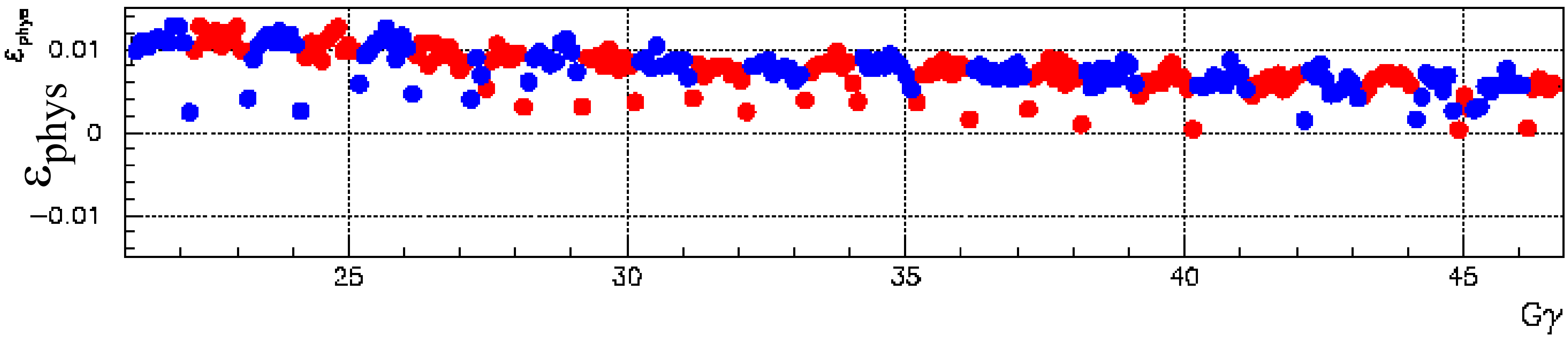
resonances:

intrinsic: $G\gamma$ = 12+ν   36-ν   48- ν   36+ν

$G\gamma = 1.91\ E_{beam}$

imperfection: $G\gamma = n$

AGS Polarization Systematics



$G\gamma = 1.91\ E_{beam}$

no false asymmetries visible

positive and negative beam polarizations give same asymmetries

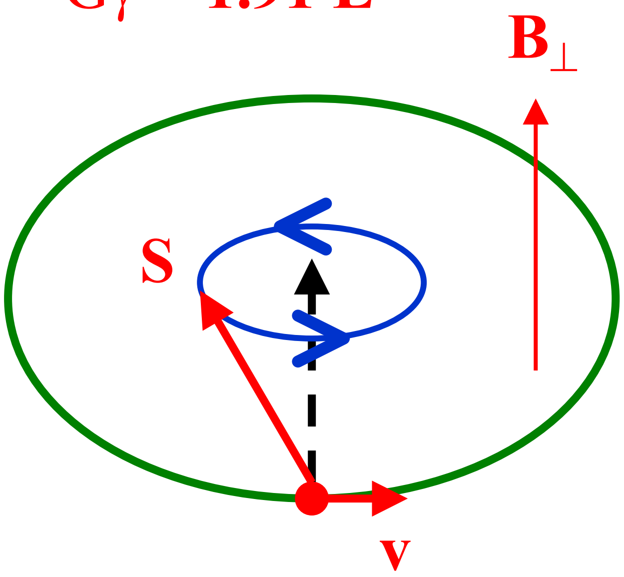
Spin Dynamics

Spin Precession in Laboratory Frame:
(Thomas [1927], Bargmann, Michel, Telegdi [1959])

$d\mathbf{S}/dt = -(e/\gamma m)\,[(G\gamma+1)\mathbf{B}_\perp + (1+G)\,\mathbf{B}_o] \times \mathbf{S}$ $\quad$ $G\gamma = \mathbf{1.91\ E}$

Lorentz Force

$d\mathbf{v}/dt = -(e/\gamma m)\,[\quad \mathbf{B}_\perp \quad] \times \mathbf{v}$



For pure vertical field:
Spin rotates $G\gamma$ times faster than motion, $\nu_{sp} = G\gamma$

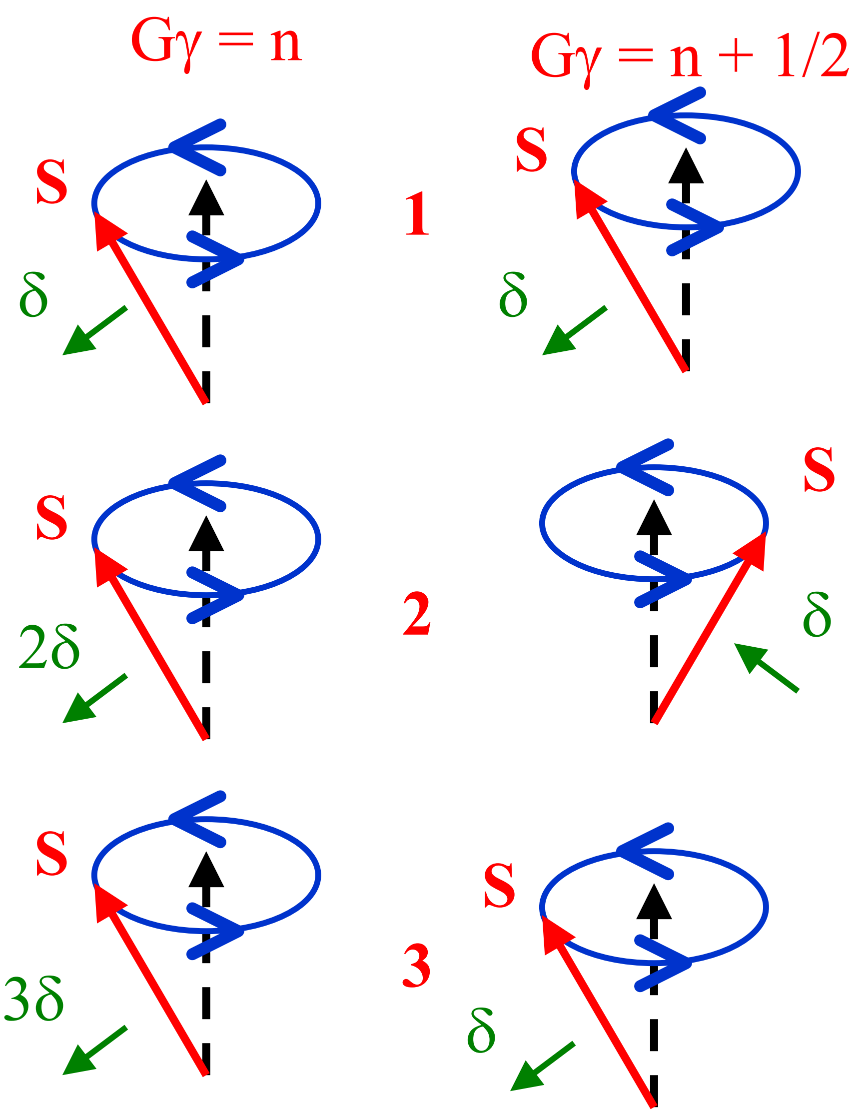
<u>Imperfection resonance</u> (magnet errors and misalignments, closed orbit errors, …):

$$G\gamma = \nu_{sp} = \mathbf{n}$$

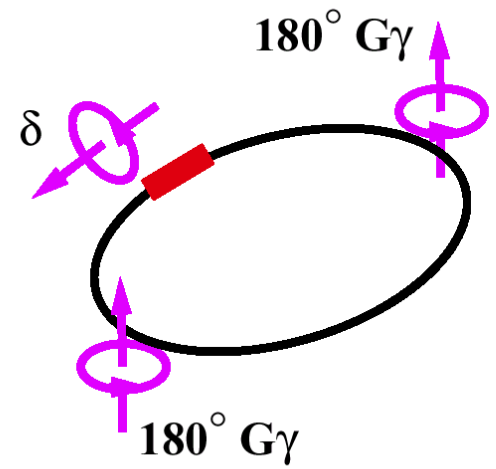
<u>Intrinsic resonance</u> (vertical focusing fields like in quadrupoles, finite beam emittance, …):

$$G\gamma = \nu_{sp} = \mathbf{Pn} \pm \nu_y$$

Imperfection Resonances: $G\gamma = n$



partial snake (AGS) = imperfection resoance

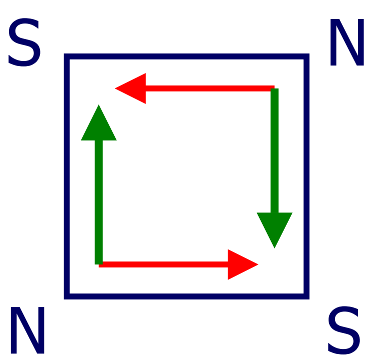


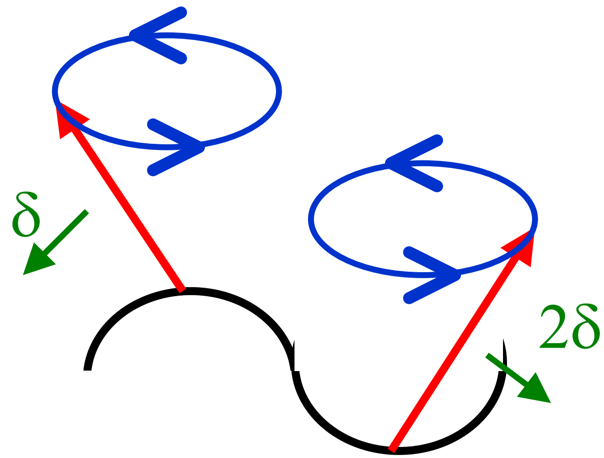
if snake sufficiently strong (5% enough in AGS) spin is fully flipped when crossing an imperfection resonance with no polarization loss

for $G\gamma \neq n$, spin "oscillates" around stable direction, which is tilted from the vertical

Intrinsic Resonances: $G\gamma = nP + \nu$

quadrupole



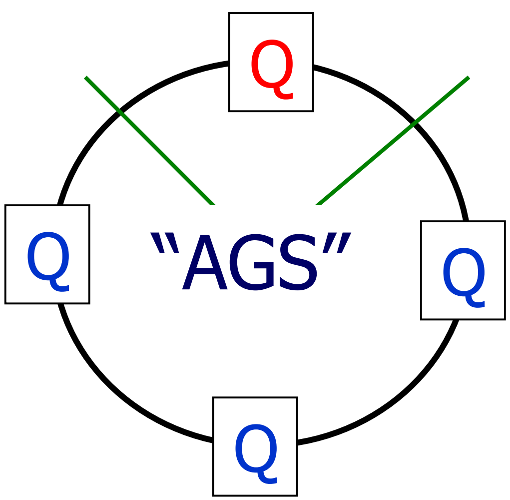


betatron oscillation of frequency ν

if spin precession "in phase" with betatron oscillation $G\gamma = \nu$ when crossing the quadrupole depolarizing kicks δ add

$\Rightarrow$ depolarizing resonance condition

FODO section

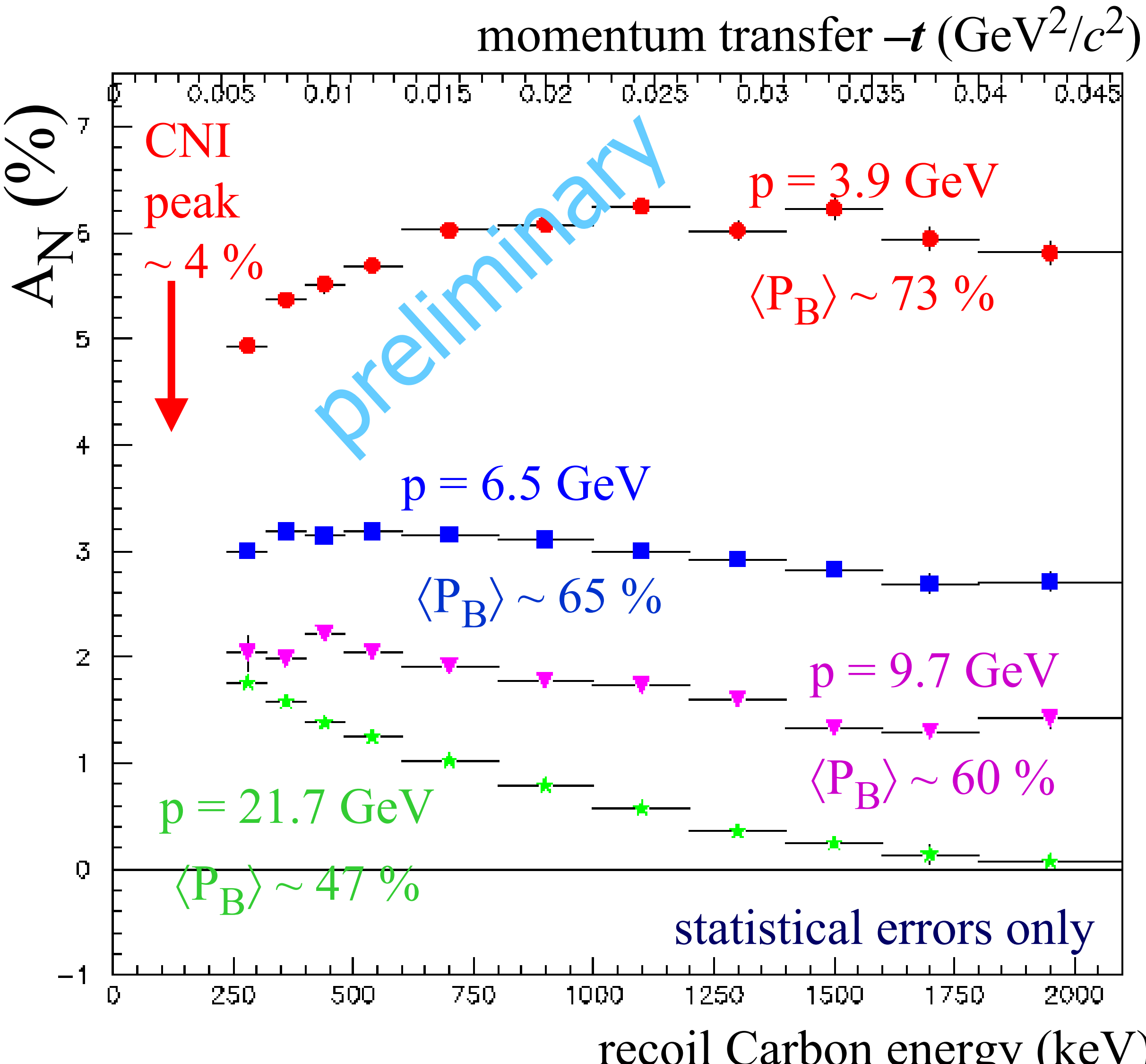


to be in phase with betatron oscillation over a closed orbit spin must precess $n + \nu$ times

in a periodic accelerator spin "in phase" with betatron oscillation when crossing same quadrupole in consecutive FODO section if $G\gamma = nP + \nu$

Polarization losses reduced / avoided by forcing a full spin reversal (flip) using an RF dipole

A_N $p^{\uparrow}C \rightarrow pC$ at 3.9, 6.5, 9.7 & 21.7 GeV

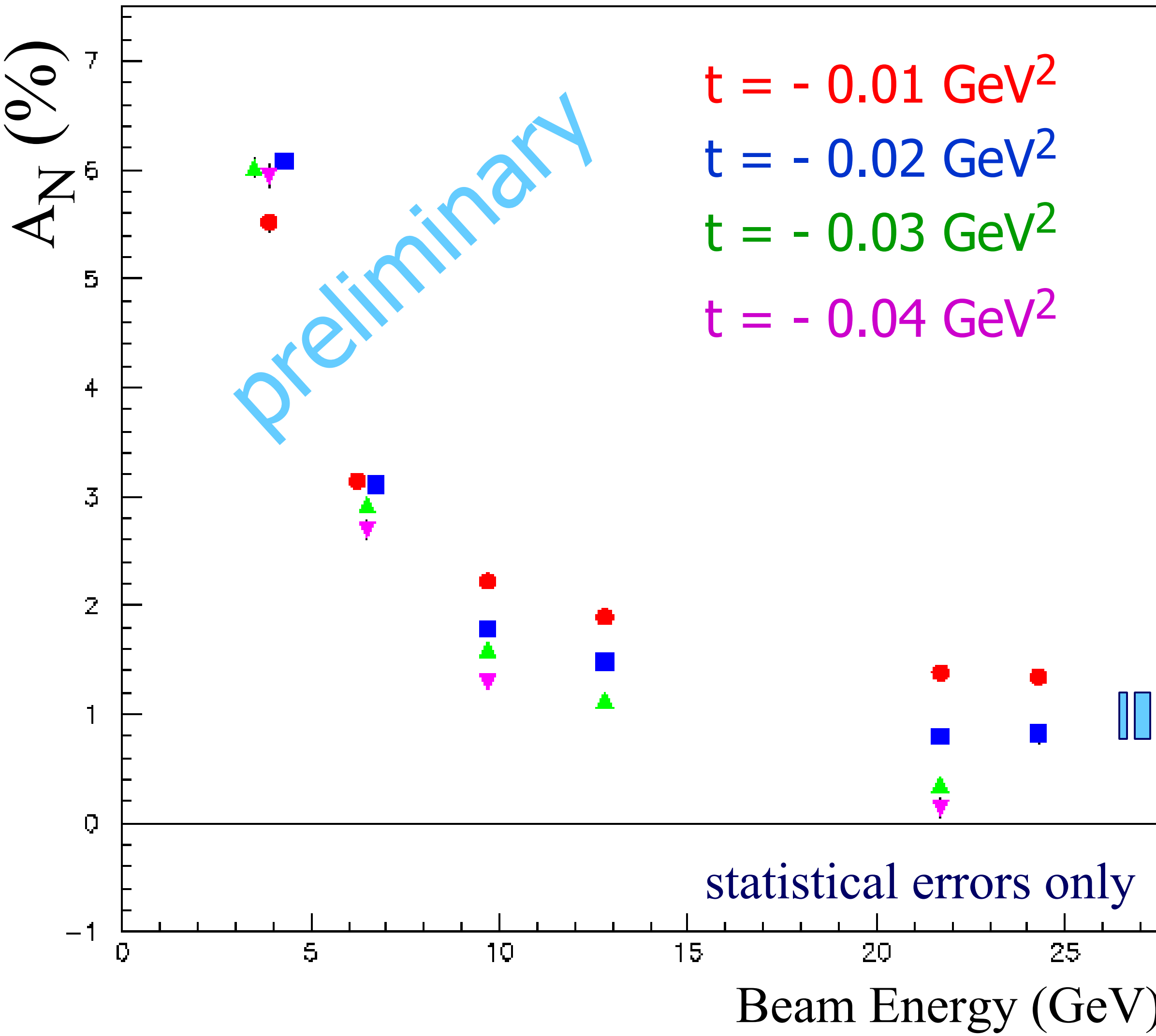


only statistical errors are shown

normalization errors:
- ~ 10 % (at 3.9)
- ~ 15 % (at 6.5)
- ~ 20 % (at 21.7)

systematic errors:
< 20 %
- backgrounds
- pileup
- RF noise

A_N $p^{\uparrow}C \rightarrow pC$: Energy Dependence



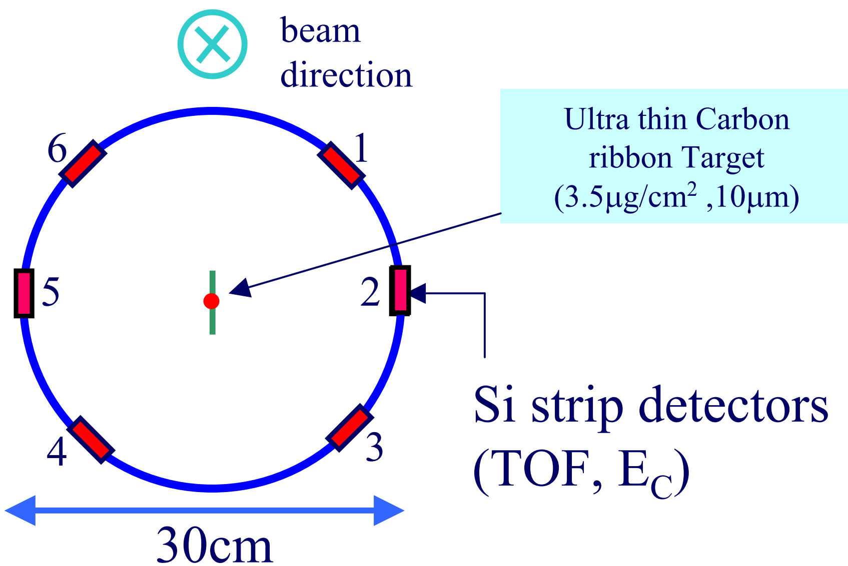
only statistical errors are shown
systematic errors as for previous slide

Asymptotic regime

E ?

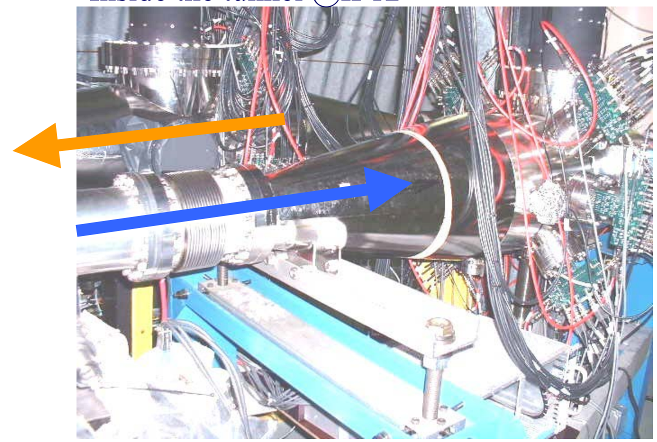
No energy dependence

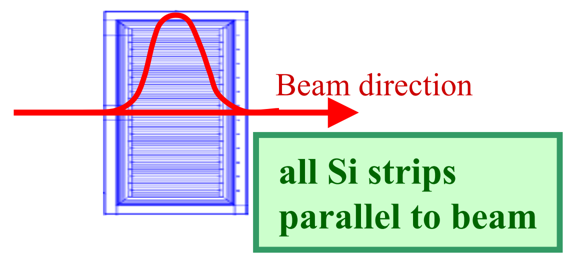
RHIC Polarimeters



RHIC x 2 rings

Inside the tunnel @IP12





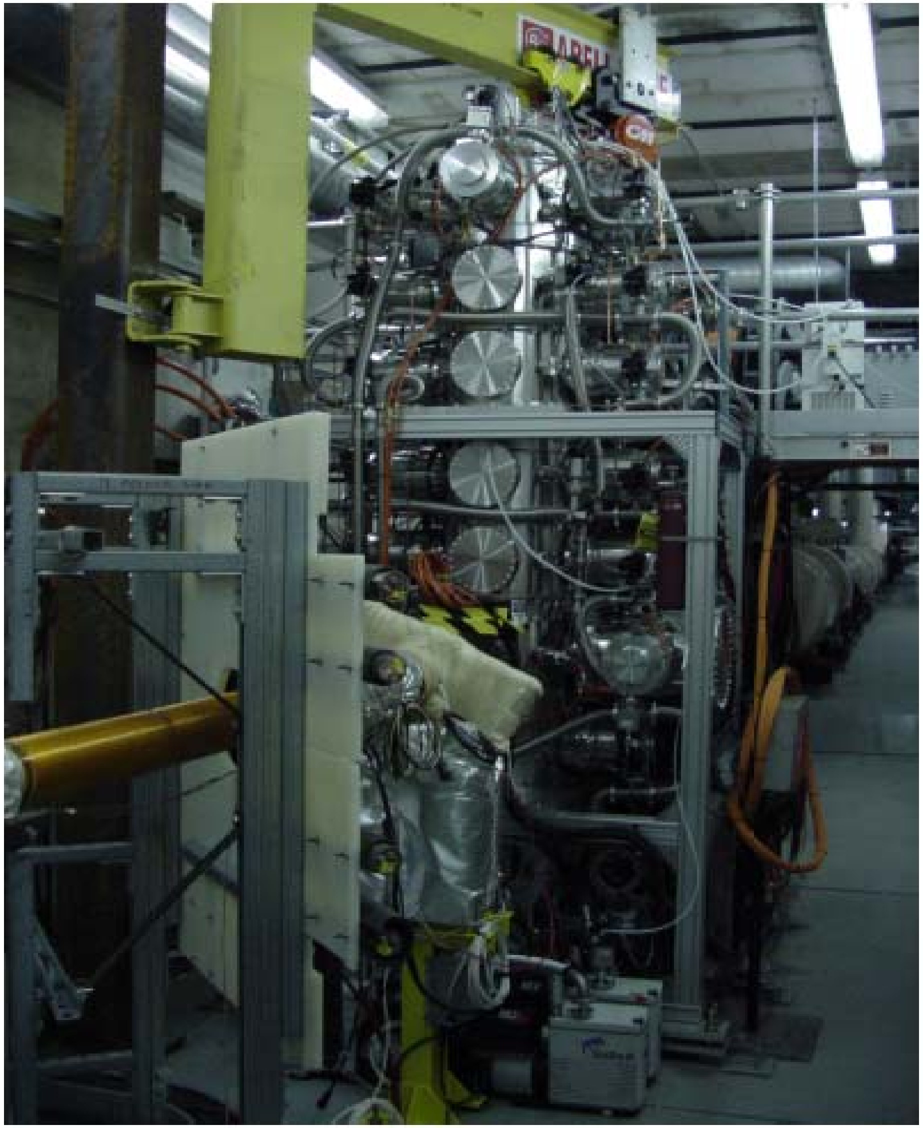
- Detectors are ***15cm*** away from target → slowest carbons can reach Si during one bunch crossing (106 nsec = 120 bunch mode)
- 2 x 72 channels read out with WFD (increased acceptance by 2 x)
- All Si strips parallel to the beam
- Si at 45 degree : sensitive to vertical and radial components of asymmetry

Polarization Measurements in RHIC

- Polarization routinely measured at injection and flattop (by now several hundred measurements)
- Detailed study of polarization behavior in RHIC
- For normalization / P_{beam} assume
  A_N (24.3 GeV) = A_N (100 GeV)
  (i.e. no energy dependence)
- Polarization profile measurements
- Several ramp measurements
- Spin tune measurements

The Absolute *pp* Polarimeter

JET in the IR



Polarized Hydrogen Gas Jet Target

- thickness of > 10^{12} p/cm^2
- polarization > 90% (~95% !)
- no depolarization from beam wake fields

Silicon recoil spectrometer

Measure A_N^{pp} in *pp* elastic scattering
in the CNI region to $\Delta A_N < 10^{-3}$ accuracy

Initially (2004) measure P_B to 10%

The Road to P_{beam}

Requires several independent measurements

0 target polarization P_{target} (Breit-Rabi polarimeter)

1 A_N for elastic *pp* in CNI region: $A_N = 1 / P_{target}\, \varepsilon_N'$

2 $P_{beam} = 1 / A_N\, \varepsilon_N''$

1 & 2 can be combined in a single measurement: $P_{beam} / P_{target} = - \varepsilon_N' / \varepsilon_N''$

"self calibration" works for elastic scattering only

3 CALIBRATION: A_N^{pC} for *pC* CNI polarimeter in detector kinematical range:

$A_N^{pC} = 1 / P_{beam}\, \varepsilon_N'''$

(1 +) 2 + 3 measured simultaneously with several insertions of carbon target

4 BEAM POLARIZATION: $P_{beam} = 1 / A_N^{pC}\, \varepsilon_N''''$ to experiments

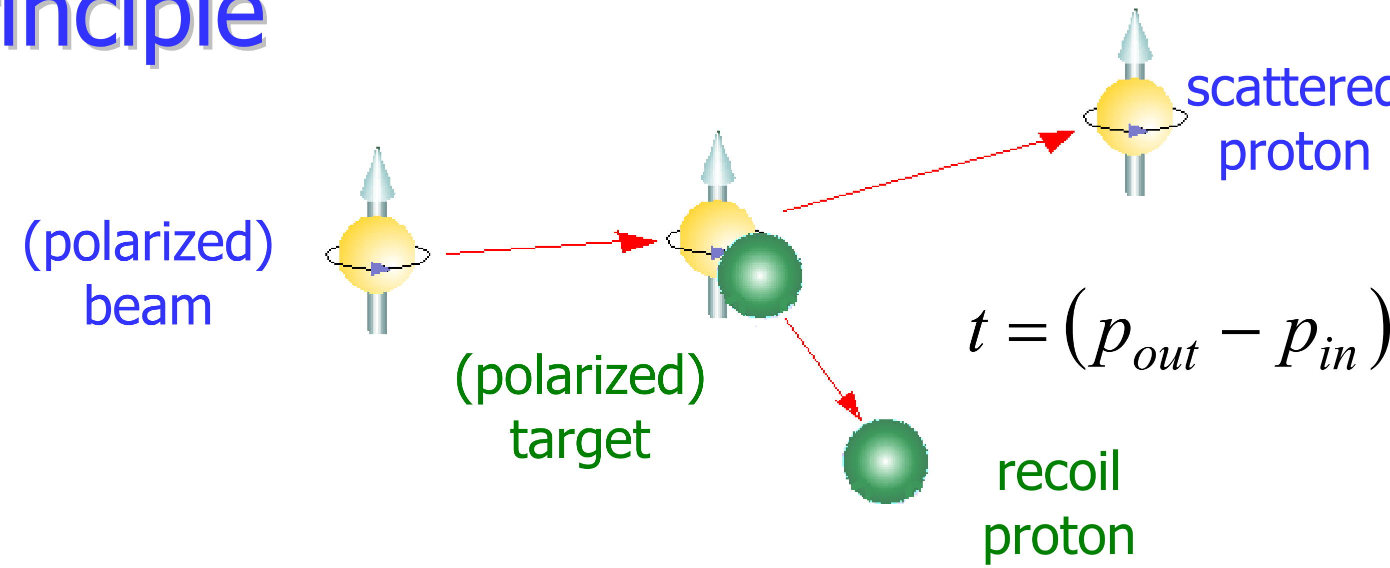
at each step pick-up some measurement errors:

$$\frac{\Delta P_{beam}}{P_{beam}} = \left(\frac{\Delta P_{target}}{P_{target}}\right) \oplus \left(\frac{\Delta \varepsilon}{\varepsilon}\right)_{pp} \oplus \left(\frac{\Delta A_N}{A_N}\right)_{pC} \oplus \left(\frac{\Delta \varepsilon}{\varepsilon}\right)_{pC} \leq 6\%$$

expected precision

transfer calibration measurement

Principle



$$t = \left(p_{out} - p_{in}\right)^2 < 0$$

$$A_N(t) = \frac{1}{P_{target}} \cdot \frac{d\sigma(\varphi+\pi)/d\varphi - d\sigma(\varphi)/d\varphi}{d\sigma(\varphi+\pi)/d\varphi + d\sigma(\varphi)/d\varphi}$$

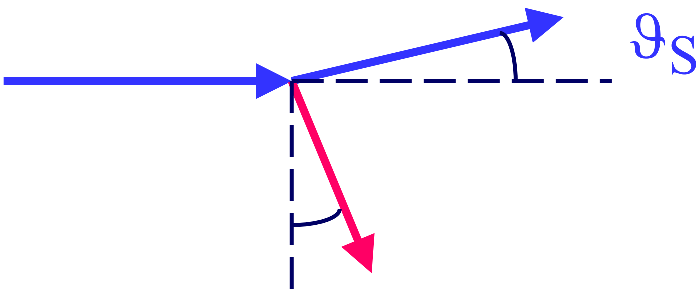
$$P_{beam} = \frac{1}{A_N} \cdot \frac{N_{left} - N_{right}}{N_{left} + N_{right}}$$

$$A_N^{beam}(t) = -A_N^{target}(t)$$

for elastic scattering only!

$$P_{Beam} = -P_{Target} \cdot \varepsilon_N^{Beam} / \varepsilon_N^{Target}$$

Kinematics



ϑ_R; E_R; tof

|t| : 0.001 – 0.02 GeV^2
ϑ_R : 1 – 5 degrees
T_{kin} : 0.5 – 10 MeV
p_R : 30 – 140 MeV/c
tof : 100 – 20 nsec (@ 1m)

essentially 1 free parameter: t (+ φ) ⇒

elastic *pp* kinematics fully constrained by recoil proton only !

$$\sin \vartheta_R \approx \left(1 + \frac{m_p}{p_{beam}}\right) \frac{\sqrt{|t|}}{2m_p}$$

$$t = -2m_p T_{kin}$$

ϑ_R & t

measure position and energy of recoil ⇒

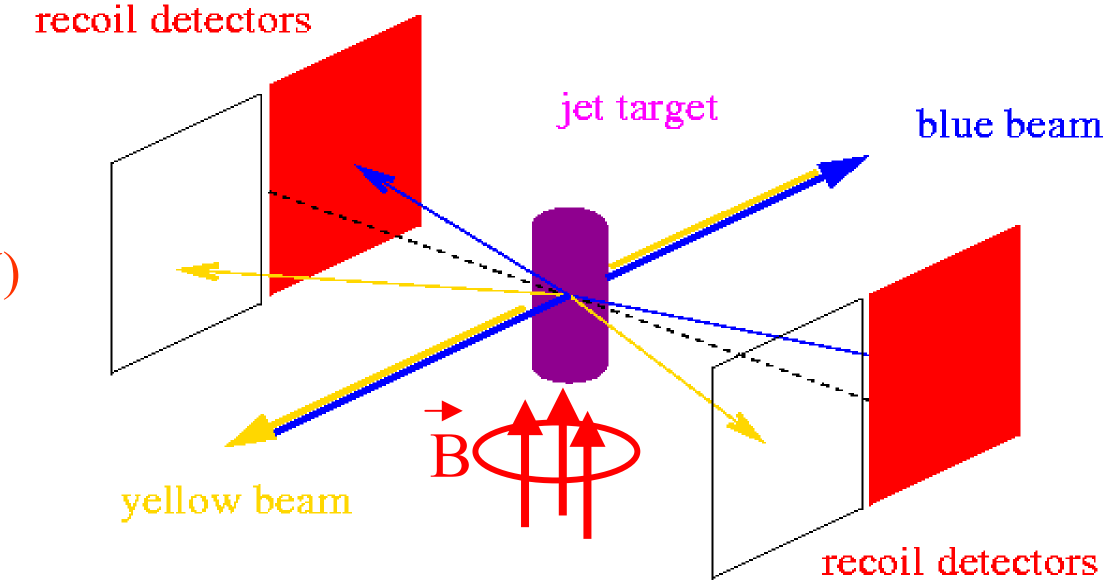
$$tof \approx 1/\sqrt{2T_{kin}/m_p} \cdot D$$

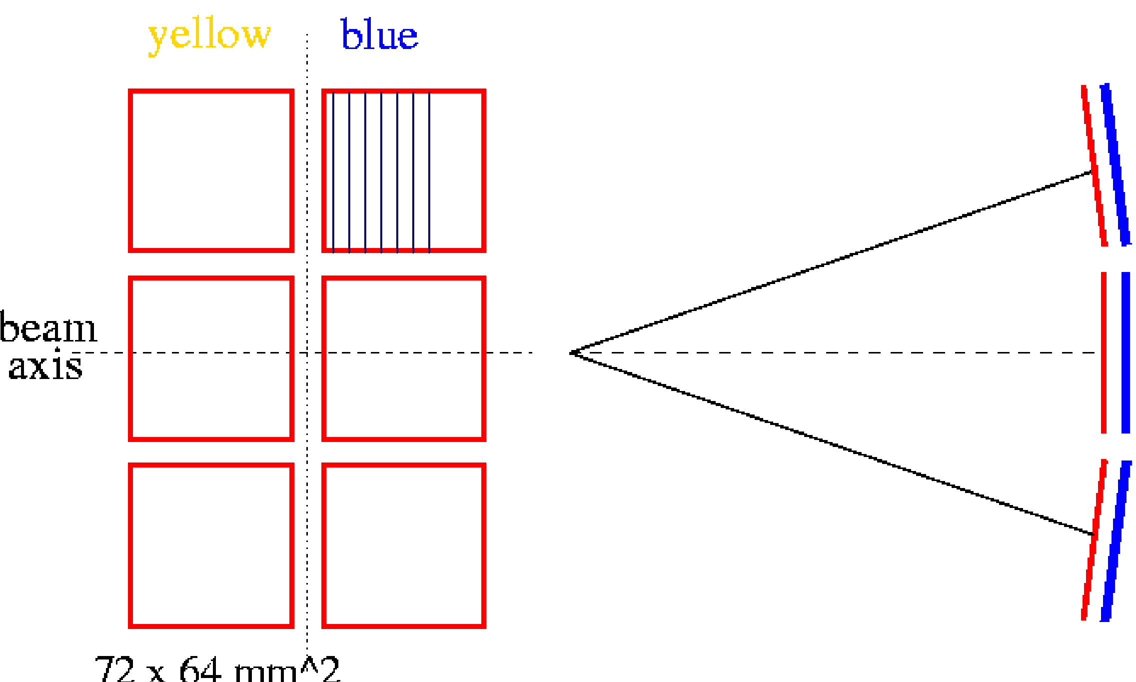
⇒ additional kinematical constraint

ϑ_R & E_R ⇒ m_{beam} (M_X); tof & E_R ⇒ m_{target}

Recoil spectrometer

6 Si detectors covering
the blue beam =>
MEASURE
energy (res. < 50 keV)
time of flight (res. < 2 ns)
scattering angle
of recoil protons from
pp -> pp elastic scattering

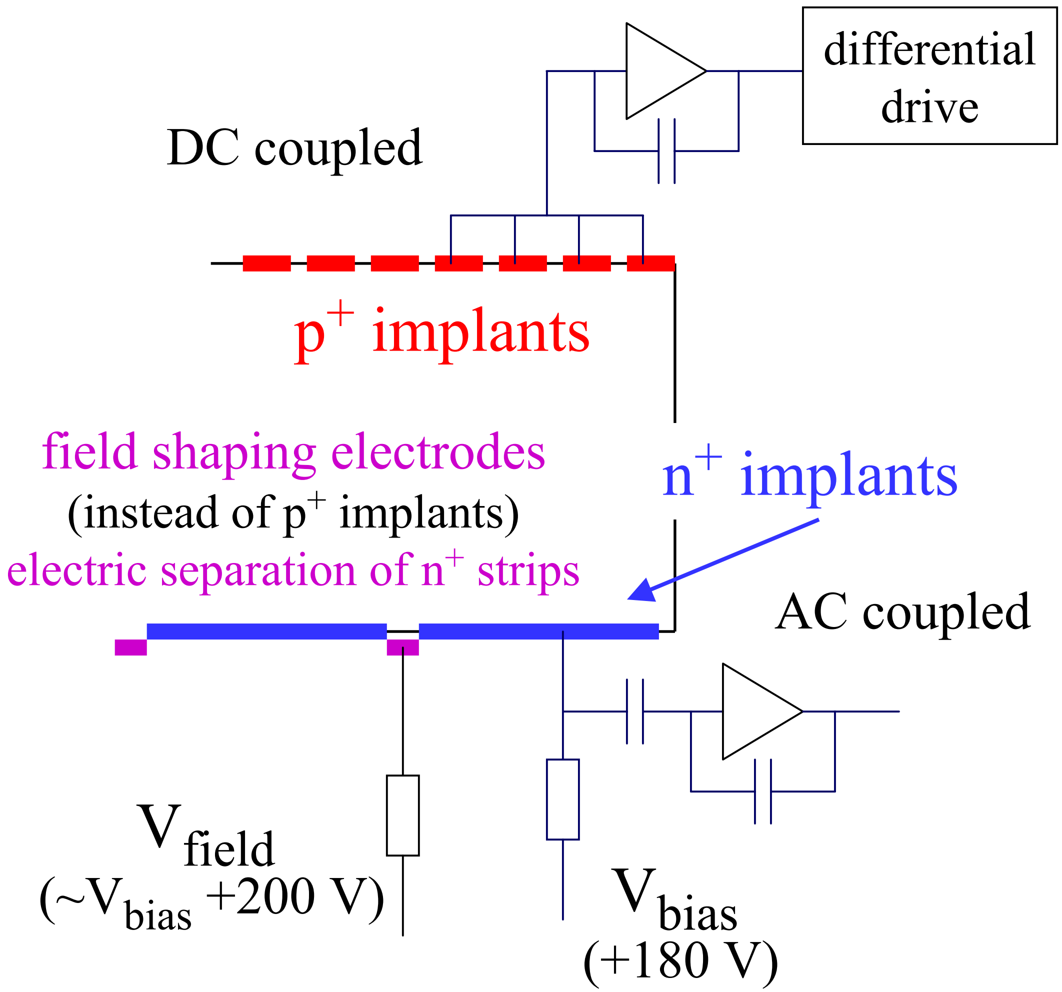




HAVE “design” azimuthal coverage

one Si layer only
⇒ smaller energy range
⇒ reduced bkg rejection power

Si Detector Design



double sided readout (opt.)
72×64 mm^2
thickness 500 microns
p^+ side pitch 1 mm
readout pitch 4 mm
n^+ side pitch 4 mm
$C \approx 20$ pF / strip (p^+ side)
80 pF / readout ch.

energy loss in dead layer less critical for protons
however same design as for pC detectors to minimize it

The Atomic H Beam Source

H_2 dissociator

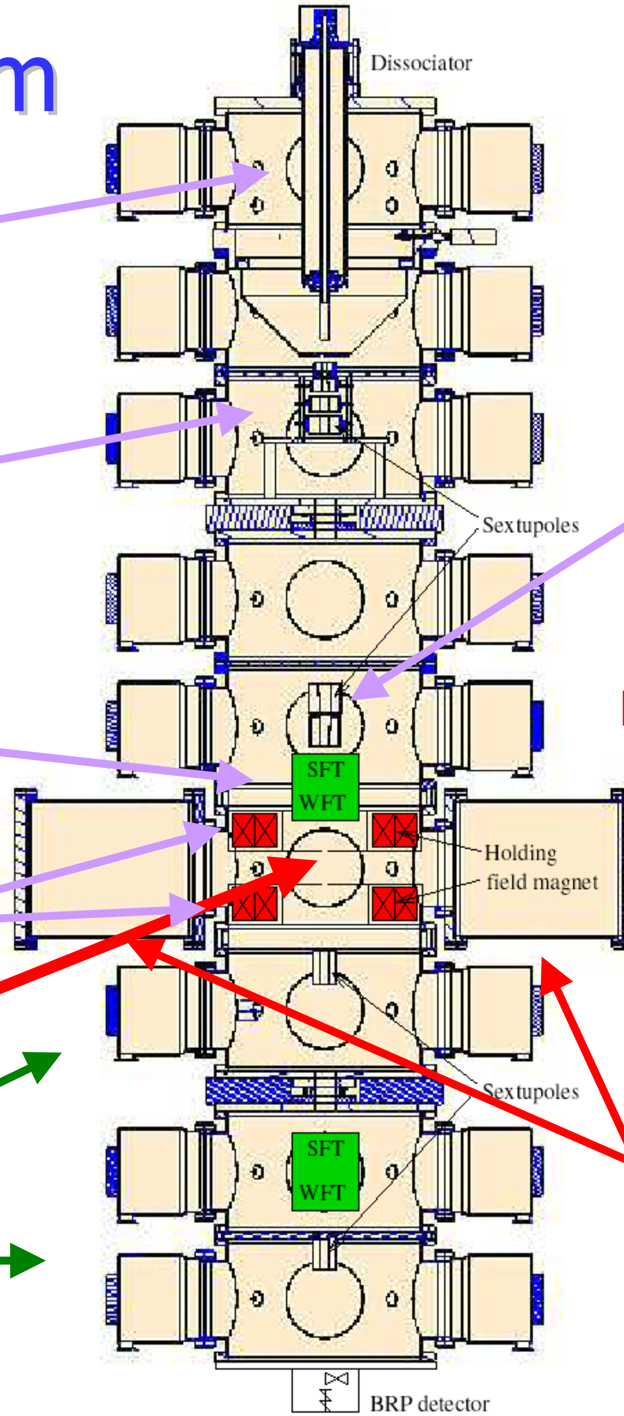
separation
magnets
(sextupoles)

RF transitions

holding field magnet

RHIC beam

Breit-Rabi
polarimeter

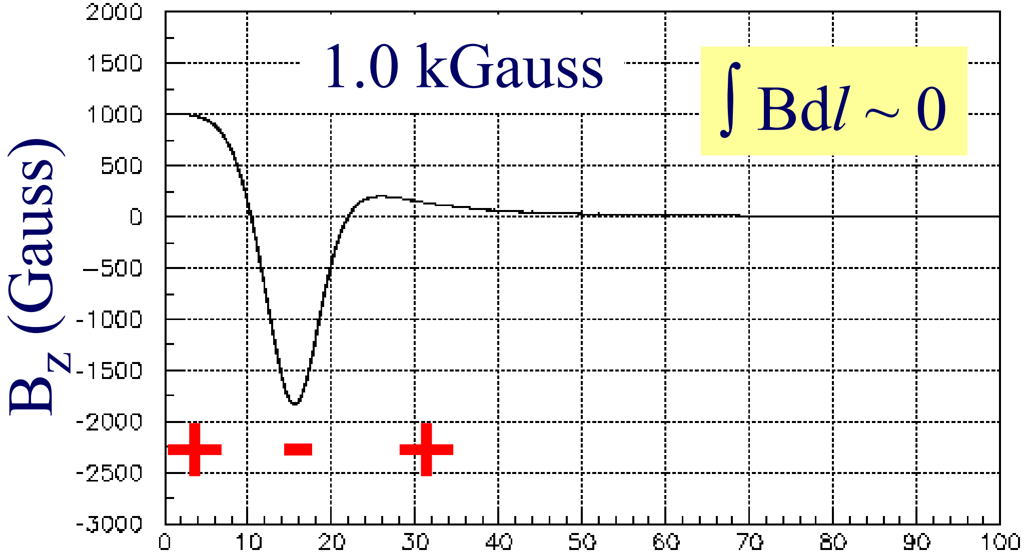


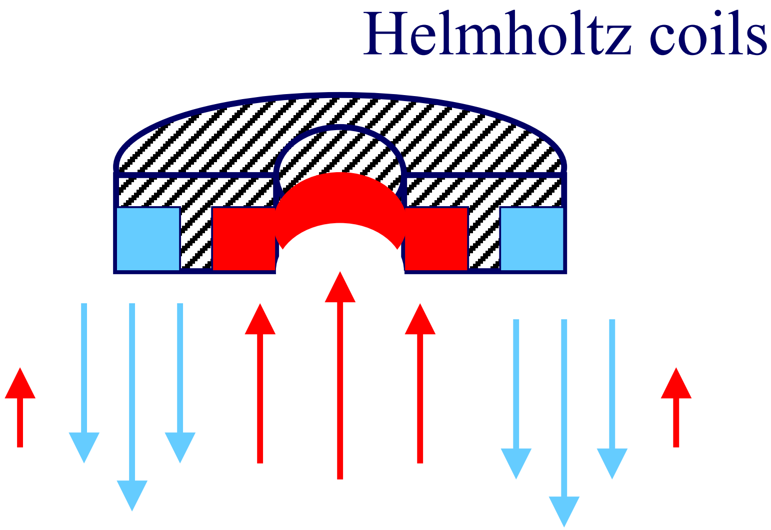
focusing
magnets
(sextupoles)

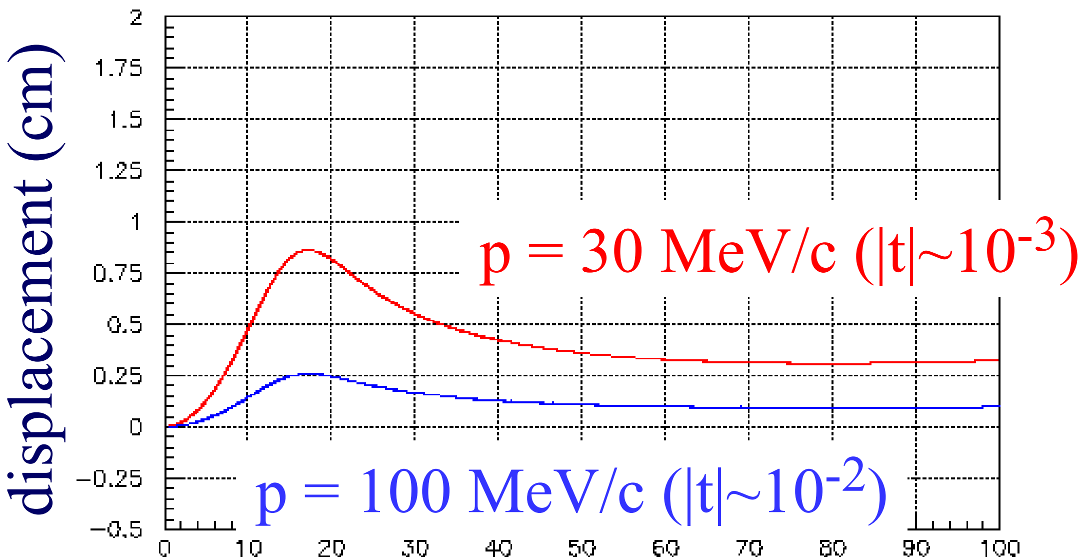
recoil detectors

p recoil arms

Jet-Target Holding Magnetic Field (1.0)





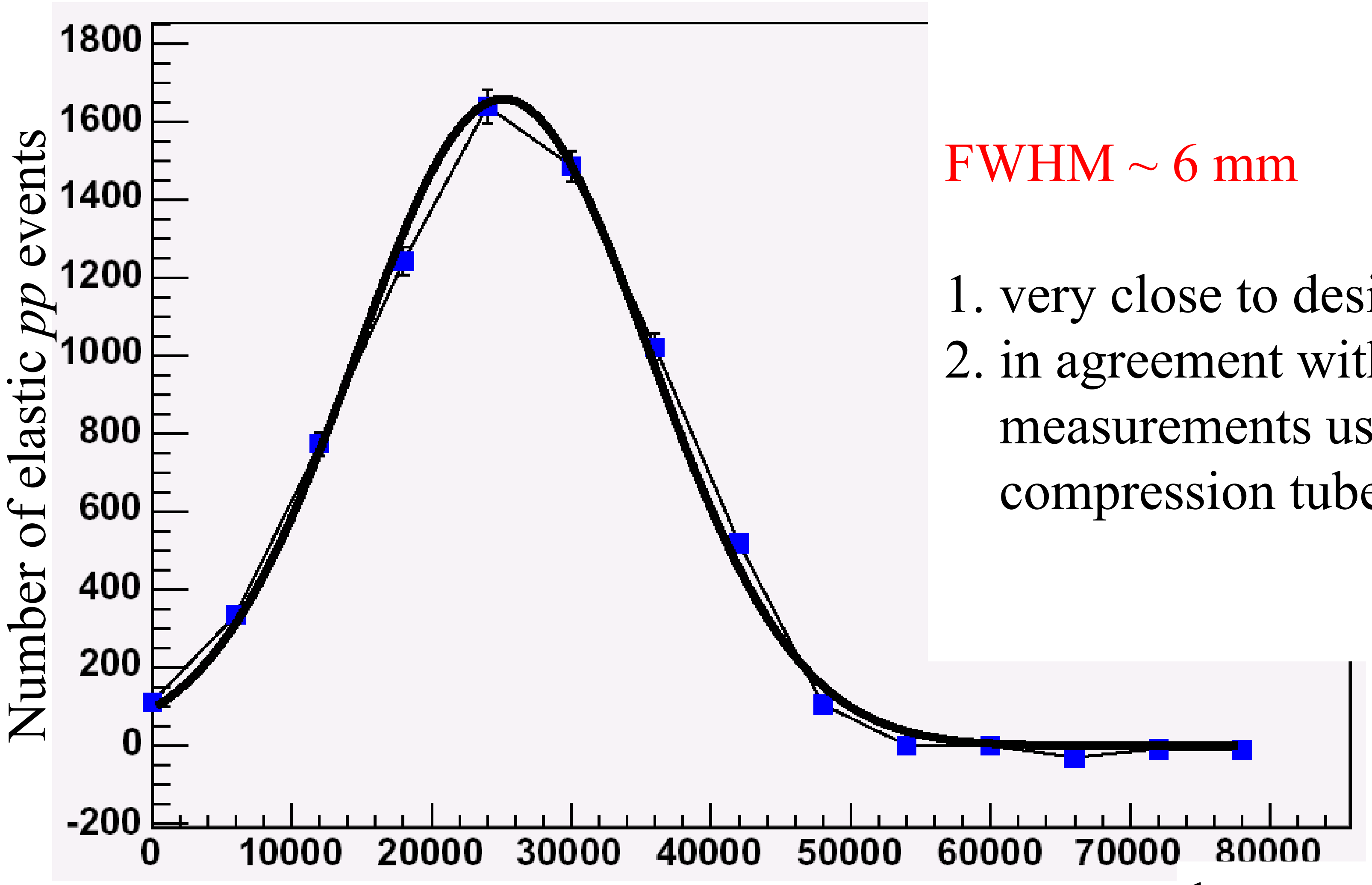


almost no effect on recoil proton trajectories:

left – right hit profiles & left – right acceptances almost equal (also under reversal of holding field)

Gas JET Target Profile

measured selecting elastic *pp* scattering events

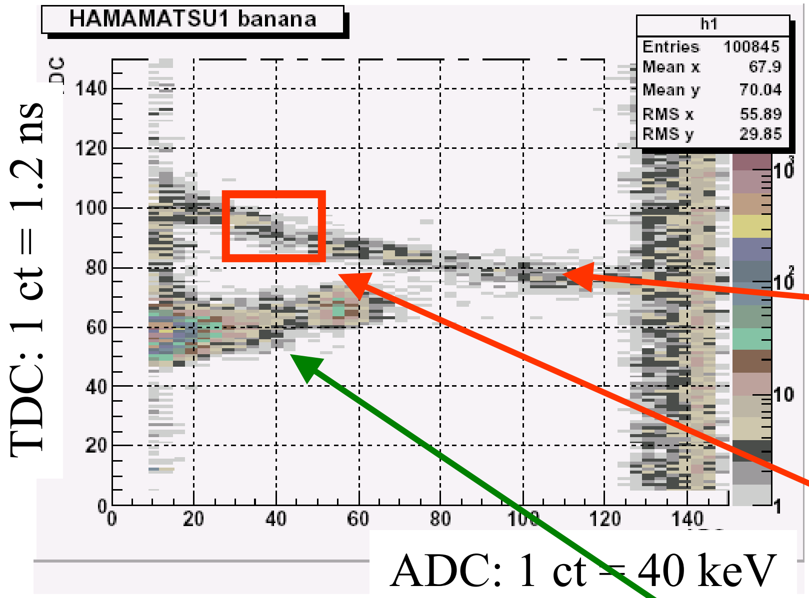


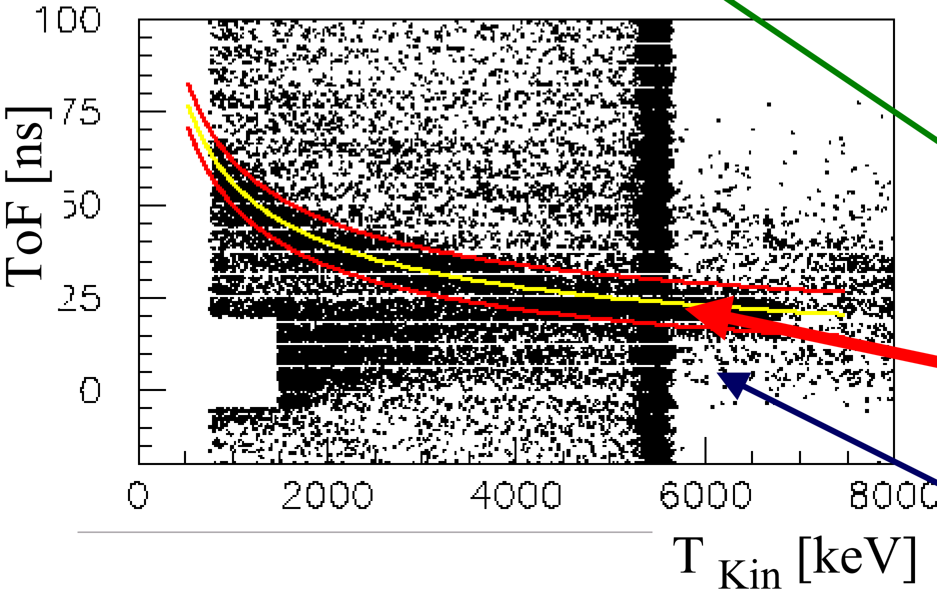
FWHM ~ 6 mm

1. very close to design value
2. in agreement with measurements using a compression tube

hor. pos. of JET
10000 cts. = 2.5 mm

Time of Flight vs. Energy recoil protons





$T_{kin} = ½\, M_R\, (\text{dist} / \text{ToF})^2$

non-relativistic kinematics

recoil protons from elastic pp -> pp scattering

CNI peak region, i.e. A_N maximal

$1 < E_{REC} < 2$ MeV

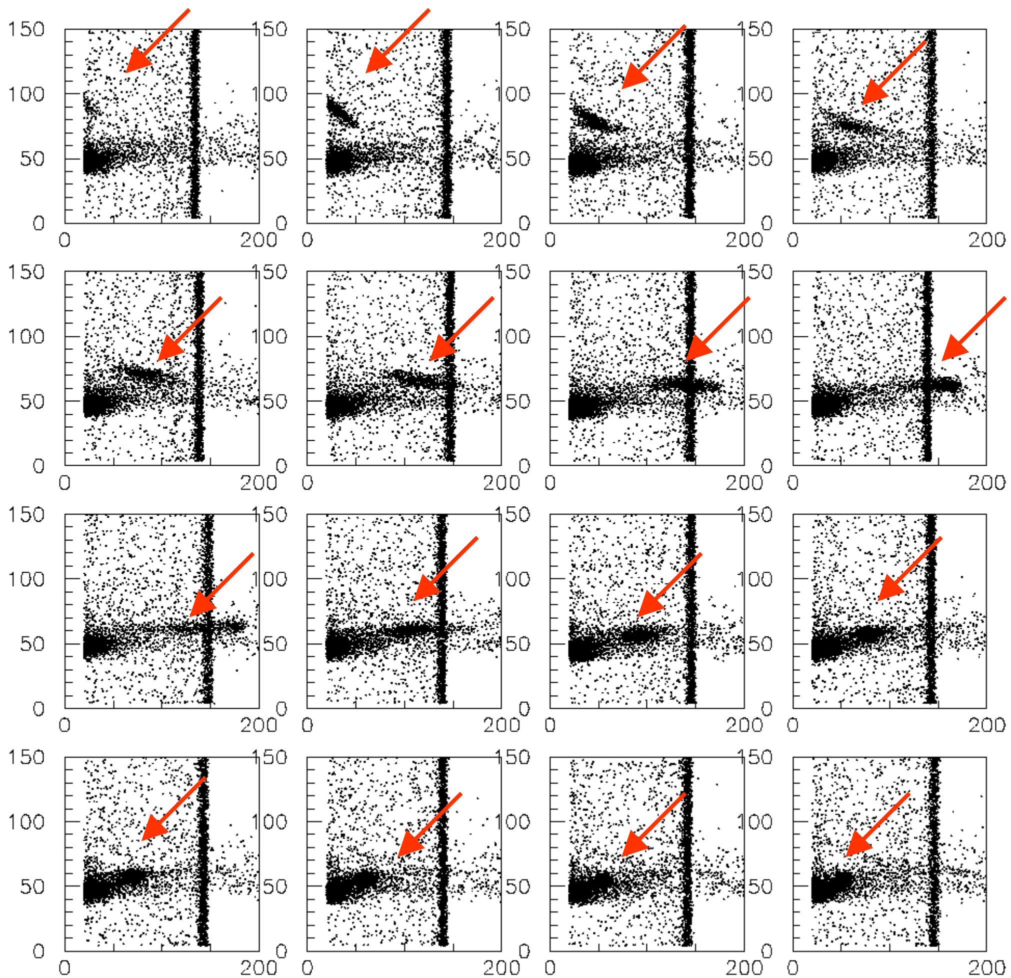
prompt events and beam gas

Δ ToF < ± 6 ns (Full Width)

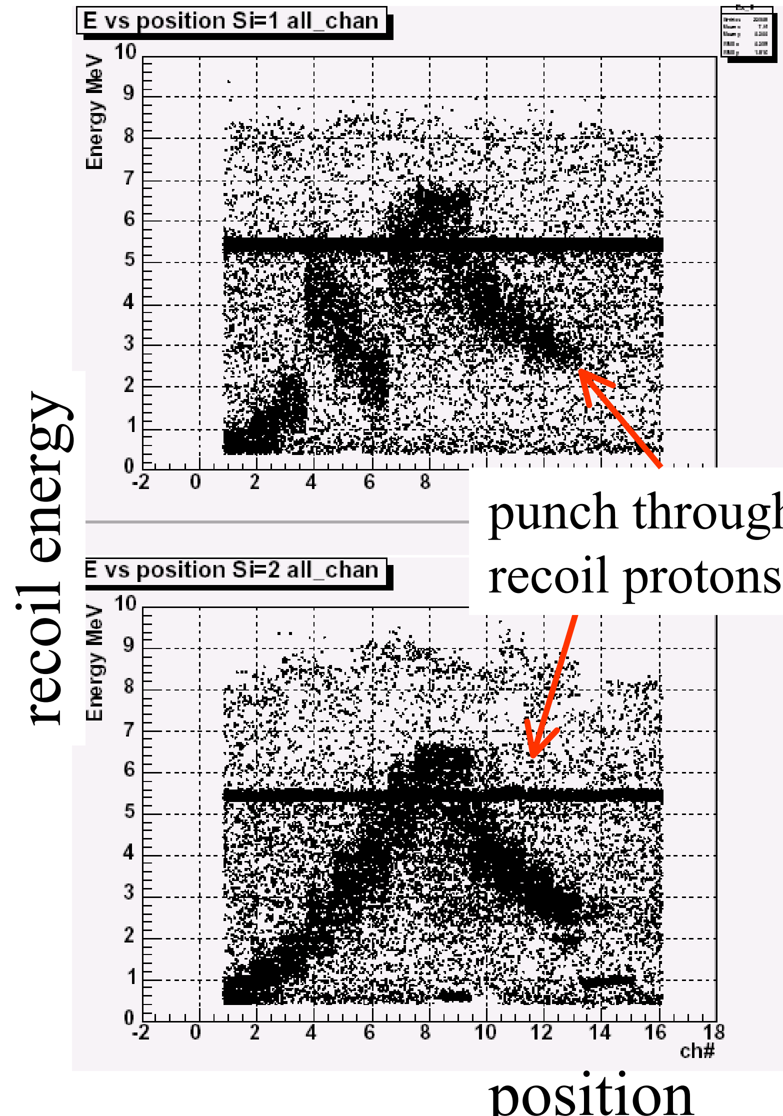
calibration α source (5.4 meV)

Energy - Position correlations

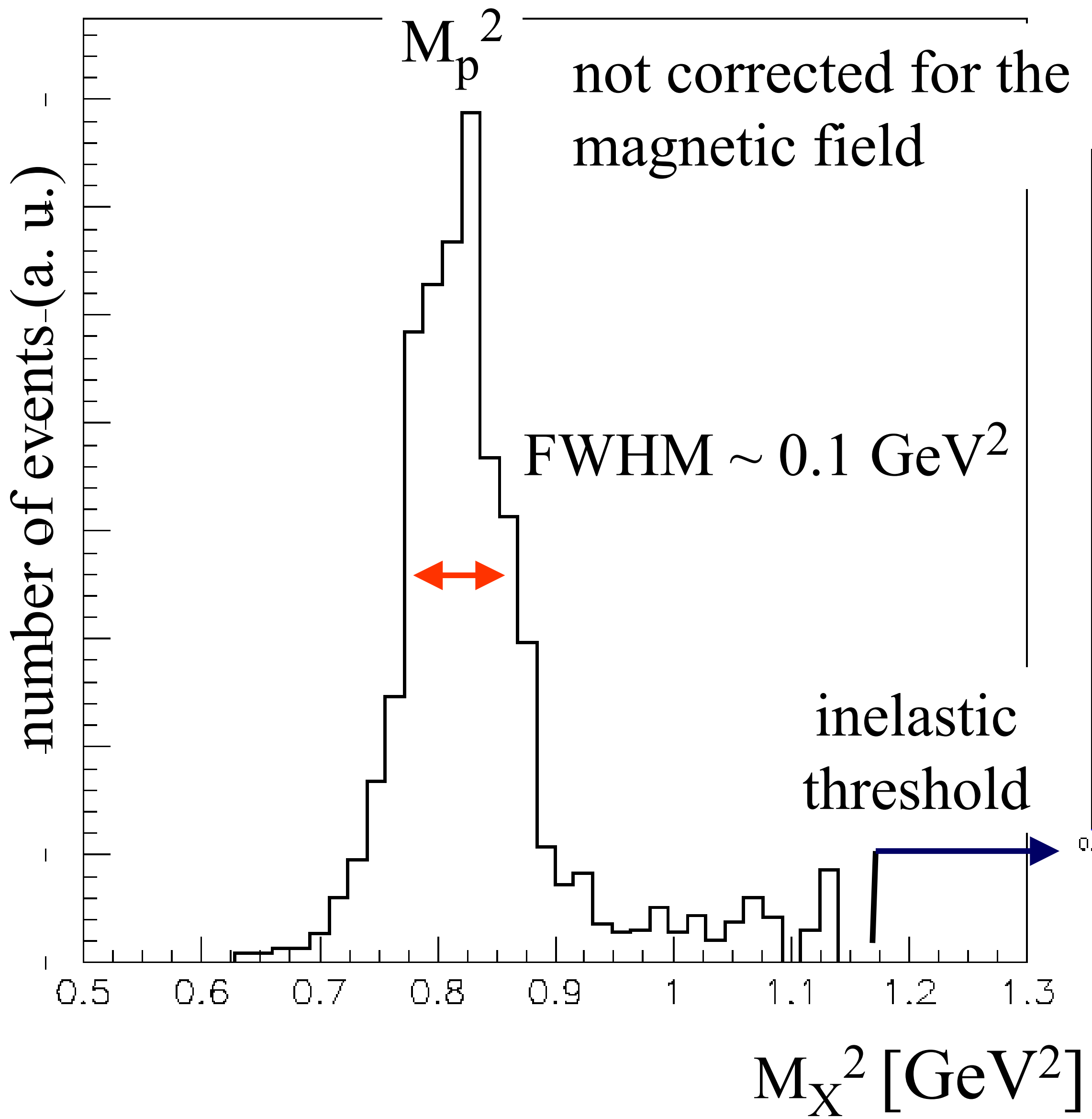
$T_{kin} \propto \theta^2$ (i.e. position^2)

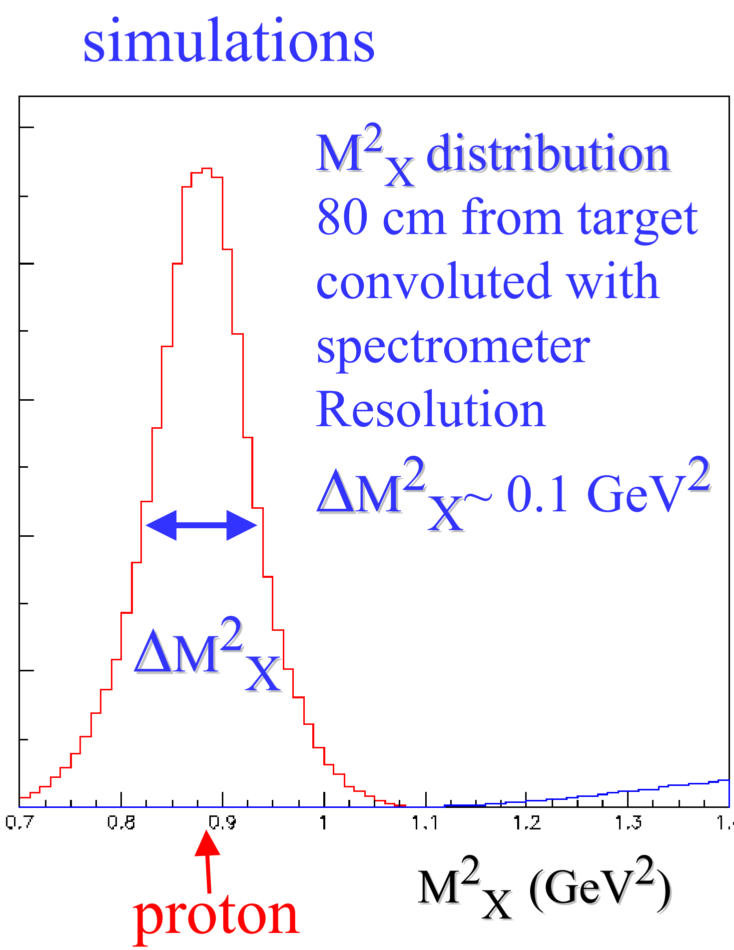


TDC vs ADC individual channels



Missing Mass M_X^2 @ 100 GeV





Statistics needed for $\Delta P / P \sim 10\ \%$

- For rate estimates we select pp elastic scattering events in
  $1 < E_{recoil} < 2$ MeV -> ~ ¼ of useful x-section
  Δ ToF < 7.5 ns

=> 2 Hz rate for 40×10^{11} protons in RHIC

- $\Delta P \sim 1/A_N \times \Delta \varepsilon_N \sim 30 \times \Delta \varepsilon_N$

  $P_{beam} = 50\ \% \Rightarrow \Delta P_{beam} = 5\ \% \Rightarrow \Delta \varepsilon_N = 0.0015 \Rightarrow$ 450 k ev

  $P_{beam} = 30\ \% \Rightarrow \Delta P_{beam} = 3\ \% \Rightarrow \Delta \varepsilon_N = 0.001 \Rightarrow$ 1,000 k ev

NB once we have P_{beam} we have to measure / calibrate A_N^{pC} for the carbon polarimeters

- Acquired statistics:
  ~ 440,000 "events" @ 100 GeV (~ 2×10^6 useful *pp* events)
  ~ 120,000 "events" @ 24 GeV (~ 5×10^5 useful *pp* events)

Summary

- polarimetry works reliably
- fast measurements of P_{beam} in few min (AGS) / 30 sec (RHIC)
- several hardware issues solved since last year
  (it is clear what needs to be improved…)
- polarized gas jet target works beautifully
  (target, recoil spectrometer, …)
- Acquired enough statistics for a first measurement of
  P_{Beam} to at least 10% (@ 100 GeV)